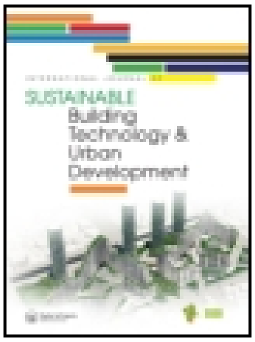

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Urban microclimate and thermal comfort modelling: strategies for urban renovation

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ABSTRACT

The urban microclimate plays an important role in building energy consumption and thermal comfort in outdoor spaces. Nowadays, cities need to increase energy efficiency, reduce pollutant emissions and mitigate the evident lack of sustainability. In light of this, attention has focused on the bioclimatic concepts use in the urban development. However, the speculative unsustainability of the growth model highlights the need to redirect the construction sector towards urban renovation using a bioclimatic approach. The public space plays a key role in improving the quality of today's cities, especially in terms of providing places for citizens to meet and socialize in adequate thermal conditions. Thermal comfort affects perception of the environment, so microclimate conditions can be decisive for the success or failure of outdoor urban spaces and the activities held in them. For these reasons, the main focus of this work is on the definition of bioclimatic strategies for existing urban spaces, based on morpho-typological components, urban microclimate conditions and comfort requirements for all kinds of citizens. Two case studies were selected in Madrid, in a social housing neighbourhood constructed in the 1970s based on Rational Architecture style. Several renovation scenarios were performed using a computer simulation process based in ENVI-met and diverse microclimate conditions were compared. In addition, thermal comfort evaluation was carried out using the Universal Thermal Climate Index (UTCI) in order to investigate the relationship between microclimate conditions and thermal comfort perception. This paper introduces the microclimate computer simulation process as a valuable support for decision-making for neighbourhood renovation projects in order to provide new and better solutions according to the thermal quality of public spaces and reducing energy consumption by creating and selecting better microclimate areas.

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Urban ; neighbourhood eco-efficiency; thermal comfort; outdoor; microclimate

1. Introduction

According to United Nations (UN) projections, the world's urban population is expected to increase by 80% by 2050, from 3.3 billion in 2007 to 6.4 billion in 2050 [1]. The rapidly increasing concentration of people in urban areas combined with a focus on the liveability and vitality of cities has led to increasing interest in the quality of open urban spaces. It is well known that thermal sensation is an important factor for the use and perception of outdoor urban spaces; taking weather conditions into account when designing cities can result in health, social, economic, and environmental benefits. Thus, by integrating social and environmental objectives, it is possible to improve the quality of life of citizens and revitalize obsolete residential areas, strengthening social interaction by improving the experiences that people have in outdoor spaces [1–6].

Urban areas are subject to undesirable thermal conditions due to changes in urban surfaces that alter the radiative exchange, humidity and thermodynamic proprieties of the environment. This causes a peculiar local urban microclimate, characterized by heat concentration in urban areas compared to surrounding rural areas, which causes alarming effects in many cities [3]. Urban areas without high climatic quality use more energy for cooling in summer and even more electricity for lighting. Moreover, high temperatures, wind tunnel effects in streets and unusual wind turbulence due to poorly designed high-rise buildings cause discomfort and inconvenience when attempting to engage in a range of outdoor activities [7].

Studies show that the use of outdoor spaces is influenced by several factors, thermal comfort among them; areas with a poor level of comfort may be avoided by

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people as a result [2,8]. Therefore, the amelioration of microclimate conditions can contribute to outdoor environmental quality, providing spaces for mutual interaction between citizens and enhancing quality of life within cities. Moreover, there are economical and environmental advantages, i.e. reducing the energy demands on buildings for heating or cooling [9,10].

Several studies have focused on thermal comfort in outdoor urban spaces. In the Rediscovering the Urban Realm and Open Spaces (RUROS) project Nikolopoulou found a relationship between microclimate conditions and thermal comfort in a Mediterranean urban environment [6]. In this work, the comfort conditions and people's experiences and perceptions were evaluated using surveys, which consisted in microclimatic monitoring, structured interviews and observations of people's behaviour in their natural environment. Other studies have focused on the significance of the links between human-biometeorology and town planning [11], such as the direct effect of the climate on people's perception at a micro scale and the diversity of microclimates in urban areas [12]. This research strives to undestrand how the weather and climate affect people in outdoor urban environments.

Studies on urban microclimates have generally been oriented to defining countermeasures for new urban areas. Nevertheless, the renovation of deprived neighbourhoods will be the main challenge of architects and urban planners in the twenty-first century, in order to bring the growth model back towards 'urban development without growth' – or, in other words, towards a more sustainable city model for existing cities. The aim of this paper is to introduce thermal comfort improvement as a target for the renovation of outdoor urban spaces through the use of microclimate computer simulation in order to support architects, urban planners and neighbours in the decision-making process for urban renovation. The study of existing urban areas, and in particular the microclimate strategies that can be applied to the renovation of rationalist urban neighbourhoods, is the main focus of this research.

2. The microclimate in the urban environment

2.1. The influence of urbanization on the microclimate

Urbanization produces different climate conditions from the surrounding rural areas, characterized by higher temperatures, diurnal temperature variation reduction, changes in wind direction and speed, different heat transference, and a peculiar rainfall balance. Regarding city sustainability, this phenomenon, known as the urban microclimate, produces a number of signigicant negative effects:

- Environmental effects: the temperature enhancement causes an increase in the demand for cooling energy in warm climates, especially in the summer. Numerous studies show a direct relation between temperature increase in city centres and CO_2 emissions and photo-oxidant gases concentration [7,13,14].
- Economic effects: The air-conditioning loads in buildings (residential and offices) create a large energy consumption as well as an increase in the costs related to the process and higher costs for more powerful mechanical equipment [7,13]. In addition, the incremental cost of supplying peak demand energy and the sanitary costs of air pollution and temperature increase should be taken into account.
- Social effects: an increase in temperature in high-density urban areas may be an important risk factor for citizens, related to health and mortality. Different studies evidence that urban populations show greater sensitivity to heat effects compared to rural regions, specially amongst vulnerable sectors (children and the elderly) [15]. Increases in urban pollution cause specific diseases such as cardiovascular disease, as well as asthma and other respiratory problems, among others. Furthermore, outdoor spaces play a key role in recreation and socialization; therefore, unfavorable microclimate conditions could affect their usage.

Passive architecture is a good alternative for reducing energy consumption and improving the sustainability of built-up spaces. However, in order to achieve better results, it is necessary to introduce passive design concepts at the urban level by using bioclimatic urban design [47].

The literature on the urban climate focuses on understanding the influence of different urban elements on microclimate formation with two main objectives: the forecasting of thermal performance and the design of palliative measures for urban spaces [16–19].

Besides considering differences with the surrounding rural areas, it is possible to notice and measure climatic differences between various zones within the same city [20,21]. Giridharan conducted extensive field measurements in order to identify the key urban design variables that influence the urban climate conditions in Hong Kong [21]. The research reveals that variables such as sky view factor, surface albedo, altitude, vegetation and the average height-to-floor area ratio are crucial for mitigating the urban climate. Other variables such as wind velocity and solar radiation are also equally crucial, but designers usually have less control over these in any built-up city. Therefore, the study reveals the strong interdependency between variables so that any intervention to mitigate microclimate effects should consider these variables within a comprehensive structure [21].

Several studies have focused on the use of vegetation as a form of improving microclimatic control in public spaces. Urban green structures can cool hot air by combining shade and evapotranspiration effects, which result in a reduction in the radiant temperature and greater control over wind velocity and direction; furthermore, plants can regenerate air, absorb the dust that falls as temperatures decrease in the evening, and filter dust and noise [22].

Each urban microclimate is the consequence of several phenomena, including the regional climatic conditions, urban morphology and human activities. Therefore, various solutions are required in order to integrate all these aspect simultaneously. Due to the complexity of providing a comprehensive database for city features and the weaknesses of theoretical atmospheric models for urban environment on different scales, there is no single unique assessment method. Mathematical models have been developed to solve a variety of urban climate problems, using major simplifications due to the complexity of the urban environment. Nevertheless, computational techniques have advanced extensively over the past two decades, allowing researchers to dramatically improve the mathematical models used to formulate solutions to large-scale problems. Among these models, energy balance and dynamical numerical approaches have resulted in the most reliable and satisfactory outcomes to date [14].

2.2. The nexus between microclimate and urban quality: thermal comfort

The thermal comfort of people in the outdoor environment is one of the factors influencing outdoor activities in streets, plazas, playgrounds, urban parks, etc. The response to thermal comfort could be unconscious, but is often the result of the different use of urban spaces and its consequent increase or decrease in isolation and social exclusion. The success or failure of an urban space also depends on its climatic conditions [6,11,23].

In recent years, many models of thermal comfort have been studied with the purpose of finding direct and indirect links between human thermal sensation and the use of outdoor spaces. Several studies have shown the importance of microclimate urban conditions in the perception of outdoor urban spaces, which can result in economic, social and health benefits if improved [24]. The design of comfortable spaces also anticipates knowledge of what is comfortable.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines comfort as 'that state of mind which expresses satisfaction with the thermal environment' [25]. Thus, the concept of thermal comfort is linked to the temperature sensation and the thermally neutral status.

A major group of biometereological models have been developed to describe thermal comfort in terms of physiological processes as well as how the heat-transfer properties of the human body are linked to local microclimatic conditions [24]. The effector responses of metabolic heat production (basal + work) result in a heat loss or gain which affects the passive system in the new body temperature. The environmental parameters and heat production levels affect the relationship between those effectors and the body temperature [26].

Studies focusing on the physiological aspect are interested in how the thermal environment affects the regulation of the human body (sweating, shivering, vascular changes, etc.) using physiological models based on human-body balance. However, the heat fluxes between the environment and the human body are not easy to simulate because, in addition to climatic parameters, other factors such as clothing and work activity come into play. Also, the relationship between global thermal sensation and changes in local conditions is not totally clear [27].

In the past 40 years, more complex multi-segmental models have been developed in order to simulate and predict the body's physiological response to various conditions in greater detail. Following a comparison between different models, the Fiala multi-node thermo physiological model was selected to form the basis of the Universal Thermal Climate Index (UTCI) [28]. The UTCI was developed as COST Action 730 of the International Society of Biometeorology with the aim of creating an internationally-recognized comfort index for people in outdoor spaces based on a comprehensive physiological model which takes into account the component of adaptation.

The Fiala model can simulate the human body with a good degree of accuracy in terms of both the local and overall physiological response. The body heat losses are calculated taking into account the characteristic inhomogeneity such as the non-uniformity of skin temperature, regulatory responses, clothing properties and environmental conditions [28]. The UTCI follows the concept of equivalent temperature (ET), which involves the reference environment with 50% of relative humidity (RH, but vapour pressure capped at 20 hPa), calm air and radiant temperature making up the air temperature. The physiological response of exposure, taking into consideration clothing insulation, has been calculated for an individual who is assumed to be walking at 4 km/h on ground level after 30 min and 120 min [28]. The UTCI defines the equivalent temperature for a given combination of air temperature, wind speed, humidity and radiation as the air temperature of the reference environment, which produce the same response. Figure 1 shows the assessment scale of the value of the UTCI ET [29].

For the evaluation of comfort in terms of external systems based on the balance of heat needed for a reasonable comfort level for skin temperature and sweat rate, it can only be used in steady-state conditions [30]. A proper evaluation must take into account the substantial differences between external and internal conditions such as exposure time, adaptation, metabolic activity and clothing. Among various existing comfort indices, the UTCI is the most suitable benchmark for comfort assessment because i) it can describe the well-being conditions of the individual, ii) it is easy to calculate using climatic parameters which can be obtained by simulation, and iii) it provides a wide range of results in order to distinguish between the diverse possible solutions.

2.3. An urban microclimate forecast using a numerical method

For the thermal behaviour analysis, the experimental methodological approach is probably one of the most widely used. However, works based on field measurements require a lot of specialized equipment and technicians, rendering them expensive and time consuming. Furthermore, the theoretical formulation is very difficult due to the many factors involved in the microclimate and,

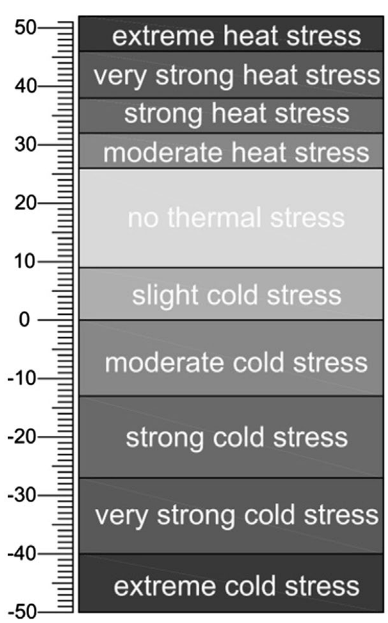

Figure 1. UTCI assessment scale. Source: Bröde, P, Fiala D, et al. and (2012) Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). International Journal of Biometeorology 56(3). p 483.

in many cases, the outcomes are not applicable elsewhere [14,16].

The numerical approach is an alternative research method that many studies are utilizing due to two main reasons:

1) The numerical model is particularly suitable for highlighting the connection between the physical urban structure, the microclimate and thermal comfort by making the translation from the results to the practical design guidelines.
2) Compared to extensive field measurements, it is faster and less expensive, and it also allows comparisons among numerous case studies and project scenarios [16,31–33].

Urban microclimate models differ substantially according to their physical basis and their temporal and spatial scale. The length scale for example can vary from a few metres to a few kilometres, and the timescale from a few seconds to seasonal variations lasting for a period of months. It is practically impossible to solve all the scales in a single model with the present available computational power. Despite this, the use of computers allows the solving of differential equations numerically with appropriate boundary conditions and pressure and temperature profiles on a predefined numerical grid [31]. On the micro scale, three-dimensional (3D) models include hydrothermal processes and energy processes. Urban canyon models are typical examples; they use simplified turbulence schemes which are combined with 3D flow modelling and 2D energy modelling. Furthermore, very few microclimate models evaluate thermal comfort, mainly due to the difficulty in determining the human body repercussions in urban areas produced by complex radiation fluxes. This problem is often caused by the use of simplified methods, in which many atmospheric processes are removed and replaced by data sets [16,31,34].

Several scholars have used ENVI-met to simulate the urban climate on the microscale. The software was developed by Michael Bruse at the University of Mainz, Germany in order to simulate the interaction between surfaces, plants and air in an urban environment. The tool has been further developed to allow the analysis of the effect of small-scale changes in urban design (pattern, vegetation, building morphology, etc.) on the microclimate under mesoscale conditions defined at the beginning of the simulation (city climate, meteorological data, etc.) [35,37].

The main model is designed in 3D with two horizontal dimensions (x and y) and one vertical dimension (z). ENVI-met is based on thermodynamics and computational fluid dynamics (CFD) using non-hydrostatic incompressible Navier–Stokes equations (Equations (1a), (1b) and (1c)) with Boussinesq Approximation (Equation (2)):

$$\frac{\partial u}{\partial t} + u_i \frac{\partial u}{\partial x_i} = -\frac{\partial p^{'}}{\partial x} + K_m \left(\frac{\partial^2 u}{\partial x_i^2} \right) + f\left(v - v_g \right) - S_u \quad (1a)$$

$$\frac{\partial v}{\partial t} + u_i \frac{\partial v}{\partial x_i} = -\frac{\partial p^{'}}{\partial y} + K_m \left(\frac{\partial^2 v}{\partial x_i^2} \right) + f\left(u - u_g \right) - S_v \quad (1b)$$

$$\frac{\partial w}{\partial t} + u_i \frac{\partial w}{\partial x_i} = -\frac{\partial p^{'}}{\partial z} + K_m \left(\frac{\partial^2 w}{\partial x_i^2} \right) + g \frac{\theta(z)}{\theta_{ref}(z)} - S_w \quad (1c)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (2)$$

To use a numerical model, the area of interest must be divided into grid cells [33–35]. An extensive list of variables provides a comprehensive description of the atmosphere, surface and soil for each cell in the model (for more information, see the 'scientific docs' on the official website, http://www.envi-met.com).

Numerical simulation is commonly used by city planners to make decisions on parameters like building density and orientation for new urban areas [34]. The results of this work have shown that the numerical approach can help designers in the implementation of neighbourhood renovation projects too. Thus, different solutions can be evaluated with the aim of local microclimate amelioration. In the context of urban design, ENVI-met has been extensively used because of its capability of combining spatial variation in complex systems and thermal comfort [33]. In this paper, it is used to simulate and compare conditions generated by modifying urban elements such as vegetation and surface materials, which are the main factors in outdoor space renovation.

3. Research methodology

The research hypothesis starts from the assumption that it is possible to define microclimatic behaviour patterns associated with urban morphology, and that microclimatic conditions affect thermal comfort in the urban environment. Thus, it is possible to mitigate the worse impacts of the microclimate through modifying the existing urban public spaces, and consequently, improving thermal comfort conditions for citizens.

The aim of this work is to explore the relations between neighbourhood renovation strategies, the microclimate and thermal comfort, thus contributing to a deeper understanding of microclimate processes and the capability to forecast them. The work is based on real case studies of different scenarios for testing the effects of the modification of urban design elements on microclimates and thermal comfort. The numerical thermal behaviour of each scenario is simulated using ENVI-met, and the results are compared in terms of thermal comfort performance using the UTCI.

Urban renovation projects are limited to passive strategies, given that the morphology, dimensions and orientation of the existing buildings cannot be modified. Therefore, this research project is restricted to the open spaces between buildings, where surface materials can be changed, green areas can be created, and shading systems can be established. For this reason, the analysis is limited to the comparison between two main strategies: a) the modification of green areas in terms of percentage and type, and b) the replacement of existing paving materials with cool materials for non-roof surfaces.

3.1. Case studies

In order to perform the simulation process, two case studies located in Moratalaz, an open-block neighbourhood of Madrid, were selected. According to Köppen[1] the climate in Madrid is defined as a Hot Steppe climate (BSh) characterized by low temperatures in the winter, hot summers and low precipitation [36]. The average temperatures in Madrid vary between 6°C in winter and 24°C in summer. During the hottest months (July and August), daily maximum temperatures exceed 30°C, with the average humidity fluctuating between 39% and 41% and precipitation less than 15 mm per month [38].

Moratalaz is a residential neighbourhood located in the east, built in the 1970s through the public housing programmes implemented after the Spanish Civil War (1936–1939). In these social housing neigbourhoods, a novel composition of superblock lots with wide pedestrian spaces, green areas and tower blocks of different heights and configurations was created. The 1970s residential expansion areas are characterized by a very innovative urban organization model based on a rational structure: residential buildings on *pilotis*, tall blocks, large green areas between buildings and the creation of tree-lined boulevards in order to provide walkable spaces containing retail outlets and services [10]. These areas can be tested as a pilot action because there are plenty of other neighbourhoods built in the same way in Madrid which also require microclimate solutions.

The two case studies in this paper are:

- The Pavones neighbourhood, characterized by 5-floor buildings on pilotis of linear growing plants and tall buildings over 11 floors, NE-SW oriented at an angle of 27° azimuth south. The public space is occupied by car-parking areas, different types of gardens, vacant spaces and a tree-lined boulevard.

- The Fontarrón neighbourhood, characterized by 5-floor buildings in open blocks, positioned in a courtyard distribution within which are green private spaces, areas with sand, and isolated trees, NE-SW oriented at an angle of 48° azimuth south (Figures 2 and 3).

To describe the neighbourhoods, some of the indicators developed by Salvador Rueda for the Special Plan for Environmental Sustainability Indicators of urban development in Seville and the Victoria-*Gasteiz* Mobility Plan are taken as a reference (see Table 1) [39].

3.2. Simulation method

The simulations for the calculation of the microclimate changes produced by urban refurbishment scenarios were conducted in ENVI-met 3.1. The main advantages of this software are:

1. Simplicity of use and low demand of time in the use of software.
2. A good representation of the transfers between vegetation and soil surface with a multilayer configuration.
3. The possibility of using a small horizontal and vertical grid with a precision of up to 1 m.
4. The low number of input parameters for the whole vegetation–soil–atmosphere system

[16,33,37,41,42]The procedure used to build the simulation models is detailed below. The software allows the user to define:

- The mesoscale conditions based on geographic location and local meteorological settings.
- The geometry of the model environment such as building morphology structure, plant and soil details.
- The simulation start date and time, the period to be simulated and the time interval for updating the model's state (see Table 2).

The model domain is organized as a rectangular area which extends along the *x*-, *y*- and *z*-axes. The dimensions and resolution of this grid are user-defined in accordance with the objective of the simulation. The vertical grid can be equidistant or telescopic. In this research work, the real morphology of case studies was determined with an extension of about 2 hectares, and was overlapped onto a square grid of size dx=3 m, dy=3 m and dz=3 m, thus creating an equivalent model for the simulation.

Some of the important assumptions made in the ENVI-met simulation process are:

1. Flat terrain.
2. Box-shaped buildings.
3. A cubic grid with a maximum resolution of 1 m.
4. Empirical initial boundary conditions in order to obtain good agreement with the average measurement data.
5. A constant wind profile during the simulation period.
6. A constant indoor temperature and no heat storage for buildings; therefore, it is not possible to take into account the emission of heat from buildings at night.

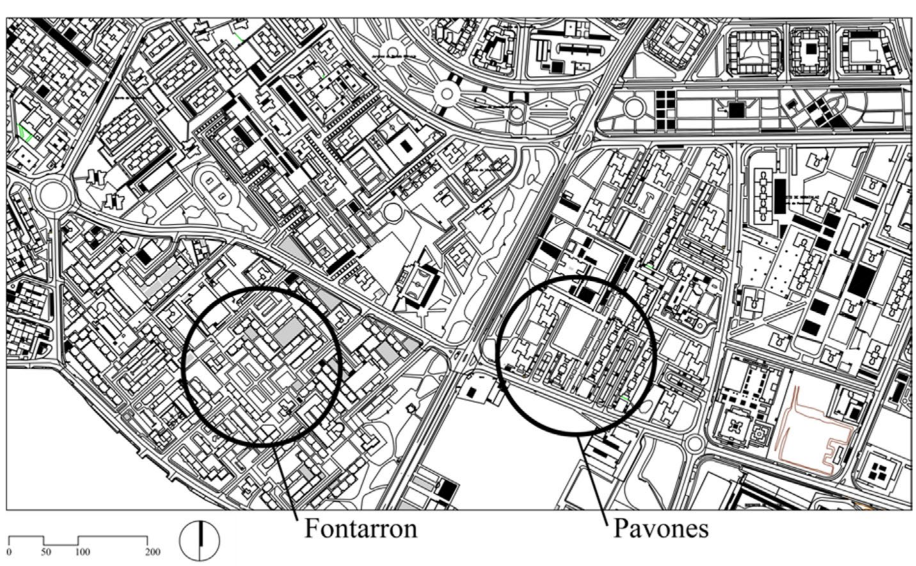

Figure 2. Image of the case study areas in Moratalaz, Madrid.

Figure 3. Images of locations from the cases studies as follows: a) Pavones parking area, b) Pavones boulevard, c) Fontarrón parking area 1, d) Fontarrón parking area 2, e) Pavones urban Canyon, and f) Fontarrón urban canyon.

7. A 1D soil model with a 5-level profile of humidity and temperature.
8. A vegetation model considering the interaction of humidity and radiation in the soil and the air. The Ag-s model [37] calculates the photosynthesis rate of the plants and from this determines the CO_2 demands and finally the state of the stomata [44].

Since the aim is to evaluate the level of thermal comfort during the daytime, the constant wind profile is valid for the case studies presented. The constant indoor temperature is not relevant to this simulation because it is based on a comparison between the current state and project scenarios, in which neighbourhood renovation will only involve outdoor spaces (green areas and surfaces materials).

The simulations were performed using the typical thermal conditions of summer and winter, simulating 24-h results every 180 min. In order to set the initial climate data, the values recorded on 15 August 2011 (summer conditions) and 21 December 2011 (winter conditions) from the Madrid-Retiro meteorological station of the National

Table 1. Details of the indicators selected for this study from the 84 indicators in [39,40].

Indicator description, objective and units	Reference Values	Pavones	Fontarrón
1.Building Density: Defined as the number of dwellings per hectare. The main purpose of this indicator is to control the density of construction, in order to avoid a diffuse city spread and congestion problems due to very high density. Building Density D (n/ha)= Dwelling (n)/ Total area (ha)	60.00-200.00	66.67▲*	142.58▲
2. *Absolute Compactness*: Defined as a building volume per square meter of urban area. The value indicates the pressure of buildings in the grid of the city. This element gives a guide for the proximity of buildings to each and the potential to condense a multi-function area into a limited space. Absolute Compactness C (m3/m2)= Building Volume (m3)/urban area (m2)	5.00-7.50	3.94▼	3.33▼
3. *Permeability index*: The aim of this indicator is to reduce impervious soil and to promote the natural water cycle. The filtration capacity is defined according to a surface filtration coefficient related to the soil type[1]. The value is defined as IP (% of m2/m2)= ∑ (area x coefficient)/total area.	0.30	0.27▼	0.23▼
4. *Percentage of roads*: This indicator shows the impact of cars on public spaces, including alternative transportation systems (bicycles and pedestrians). Percentage of roads (%)= ∑road for motorized(sm)/total road(sm).	25%	57%▼	37%▼
5. *Number of trees per built square meter*: The intent of this indicator is to ensure a minimum number of trees are situated in the urban area, according to the urban grid. This value should change with the urban typology: Trees per m2: nº of trees/ area (m2).	1t/20m2	0.09▼	0.15▼

Notes: [1]Surface filtration coefficient:
- Impervious soil = 0.00
- Partially impervious soil = 0.30
- Semi-impervious soil= 0.50
- Green area without connection with natural soil = 0.50
- Green area with connection to natural soil = 0.70
- Green area on natural soil = 1.00

Source: S. Rueda, "Special Planning of Environmental Sustainability Indicators for Urban Activities in Seville", Gerencia de Urbanismo. Ayuntamiento de Sevilla, Barcelona, 2006.

Table 2. The primary input parameters used in the ENVI-met simulation.

Type	Parameter	Value
Air temperature	Initial temperature atmosphere (K)	300
Wind	Wind speed in 10 m *ab.* ground (m/s)	2.24
	Wind direction	21
	Roughness length at reference point	0.10*
Humidity	Specific humidity in 2500 m (g water/kg air)	8.89
	Relative humidity in 2 m (%)	41
Location	Location	Madrid
	Latitude (°)	40.23*
	Longitude (°)	−3.43*
Wall	Thermal resistance ([m^2 K]/W)	0.8*
	Albedo	0.4*
Roof	Thermal resistance ([m^2 K]/W)	1.0*
	Albedo	0.3*

*Default ENVI-met value used.

Spanish Agency of Meteorology (AEmet) was used (see Table 3). According to the data available (Madrid-Retiro 2011) , the simulation days are selected because they are representative of summer and winter conditions.

This initial study was essential in order to identify the most critical hours during the day with respect to thermal comfort conditions, which correspond to 3:00 p.m. in the summer. The most critical condition is used for the evaluation and comparison of numerous hypothetical project scenarios (see Table 4). This selection was made firstly because of the need to obtain a hypothesis results that are easily comparable to one another, and secondly due to the need to mitigate the maximum conditions of thermal discomfort [14,27]. Furthermore, several studies showed the direct relationship between elevated mortality levels and high temperatures, especially regarding people over 65 years old. Miron et al. studied the time trend for the maximum temperature of the minimum organic-cause mortality in Castilla-La Mancha (Central Spain) for the period 1975 to 2003, and ascertained that the increase in mortality is attributable to the decrease in comfortable temperatures [45]. Also, according to the projections of global warming due to climate change, summer

Table 3. Weather data collected in the Madid-Retiro meteorological station.

	21 December 2011			15 August 2011		
Time	**Ta (°C)**	**RH (%)**	**W (m/s)**	**Ta (°C)**	**RH (%)**	**W (m/s)**
0	3.91	50	1.7	24.96	26	1.2
3	3.96	71	1.6	22.17	35	1.1
6	4.02	68	1.7	19.65	42	0.9
9	2.41	59	1.6	19.03	45	0.8
12	5.38	66	1.9	23.56	35	1.2
15	7.39	45	1.8	27.62	24	2.1
18	6.56	45	1.6	29.93	18	2.3
21	4.76	53	1.7	28.94	19	1.8

Note: RH = relative humidity; Ta = air temperature; W = wind speed.
Source: data provided by AEMET (http://www.aemet.es/es/datos_abiertos/catalogo).

Table 4. Results for the thermal comfort assessment of the two case studies for summer conditions.

	Parking area					Urban canyon				
Time	**Ta (°C)**	**Tmrt (°C)**	**RH (%)**	**W (m/s)**	**UTCI (Ceq)**	**Ta (°C)**	**Tmrt (°C)**	**RH (%)**	**W (m/s)**	**UTCI (Ceq)**
Pavones										
12:00 a.m.	21.18	15.27	86	1.40	**20.40**	21.48	15.06	96	1.49	**21.10**
3:00 a.m.	20.48	13.95	86	1.15	**19.60**	20.21	13.90	97	1.44	**19.70**
6:00 a.m.	19.78	13.27	86	1.13	**19.10**	19.23	13.07	98	1.42	**18.50**
9:00 a.m.	21.39	60.62	80	0.88	**33.60**	21.51	20.80	97	1.31	**23.20**
12:00 p.m	29.35	67.70	62	0.96	**40.10**	29.65	67.08	75	1.30	**41.00**
3:00 p.m.	30.85	70.27	60	1.13	**41.70**	31.26	62.73	73	1.47	**41.60**
6:00 p.m.	28.10	63.36	68	1.25	**38.20**	28.00	27.00	85	1.57	**30.70**
9:00 p.m.	23.60	17.38	77	1.20	**22.90**	23.65	17.08	93	1.55	**23.80**
Fontarrón										
12:00 a.m.	23.52	15.00	66	0.54	**22.00**	22.90	15.03	70	1.47	**20.70**
3:00 a.m.	22.29	14.12	70	1.30	**20.50**	22.99	14.22	66	1.45	**20.30**
6:00 a.m.	21.91	22.62	66	0.50	**22.90**	21.91	13.52	70	1.40	**19.50**
9:00 a.m.	23.15	64.99	59	0.70	**34.90**	23.04	20.60	64	1.20	**22.40**
12:00 p.m	26.42	72.77	61	0.60	**39.20**	28.50	67.00	59	1.30	**38.70**
3:00 p.m.	27.60	75.10	61	0.60	**40.06**	29.87	69.51	57	1.46	**40.30**
6:00 p.m.	26.80	52.42	62	0.65	**34.50**	27.71	51.59	63	1.55	**34.30**
9:00 p.m.	24.51	17.51	64	0.50	**23.40**	24.11	16.90	67	1.50	**22.20**

Note: RH = relative humidity; Ta = air temperature; Tmrt = mean radiant temperature; UTCI = Universal Thermal Climate Index; W = wind speed. The worst thermal comfort conditions occurred at 3 p.m. in both cases.

mortality will increase substantially while winter mortality will decrease [45,46].

This research focuses on the thermal behaviour in the interstitial space between buildings. Thus two main aspects were focused on: surface paving materials and green areas.

An initial approach that can be used to reduce the negative effects of a microclimate is to work on the horizontal surface materials: the streets, squares, parking areas and even roofs that cover a significant percentage of urban surfaces.

In recent years, several studies have investigated the use of cool materials. Cool pavements refer to surface materials that tend to store less heat and have a lower surface temperature compared with traditional materials. Different strategies are available for implementing cool pavements. The primary methods are the use of highly reflective materials that reduce heat absorption or composite structures that emit a lower level of heat at night. Other systems are based on the use of pervious materials in which evaporation contributes to temperature decreases [47].

Unquestionably the most effective measure for reducing unfavourable microclimate conditions however is the use of green areas and trees. The use of natural soil and trees has both direct and indirect effects on the urban microclimate. The direct effects include the creation of shade and wind protection, whilst the main indirect effect is the evapotranspiration of the plants [2,14,21,48].

3.3. Simulated scenarios

Different renovation proposals were tested using the two case studies (Pavones and Fontarrón) and the results delivered by the project scenario simulations were compared to the current state. For the selection of surface materials, the scenarios are as follows:

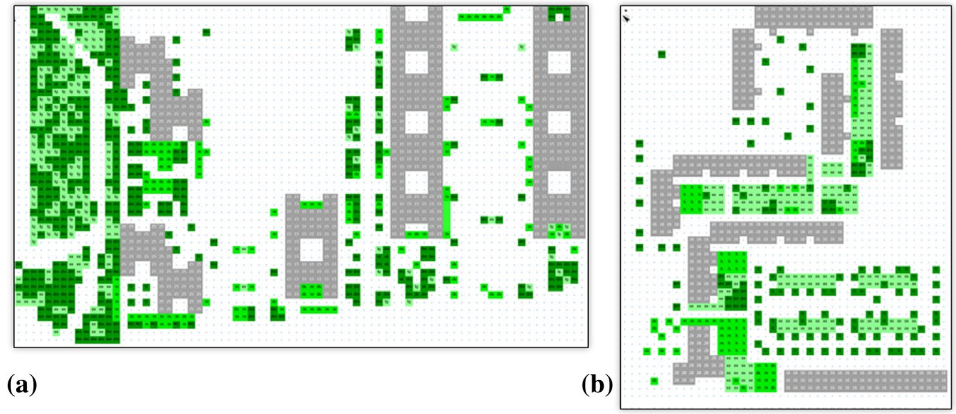

Figure 4. ENVI-met 3.1 simulation model of a) Pavones and b) Fontarrón. Source: Author Elaborate using.

(1) Replacing asphalt soil with white asphalt for roads and semi-pervious soil with turf block for parking places.[2]
(2) Replacing asphalt soil with Perfect Cool for roads and semi-pervious soils with turf block for parking places.[3]
(3) Reducing green areas and pervious soil by replacing them with traditional materials (asphalt and concrete).

And for the green areas, the scenarios are:

(4) Improving the green areas using tall trees (20 m tall with a leaf area density of 0.3) for up to 30% of the total surface of the open areas.
(5) Improving the green areas by using shrubs (1.5 m tall) for up to 30% of the total surface of the open areas.
(6) Replacing impervious soil with grass.

The analysis was conducted by comparing the parameters of weather – air temperature (Ta), mean radiant temperature (Tmrt), relative humidity (RH%) and wind speed (W) – and thermal comfort (UTCI) for the actual conditions and the six scenarios described above. Conditions from 9:00 a.m. to 9:00 p.m. are taken into account to define the most unfavourable conditions.

4. Results

The analysis of the thermal conditions for the six project scenarios compared the scenario simulation outputs with the current state for the air temperature (Ta, °C), mean radiant temperature (Tmrt, °C) and UTCI (Ceq). The vertical definition of all the model domains considers a 0.4 m vertical grid size in the five lowest grid cells. The section at 1.2 m from the ground (grid 3z) was chosen because it represents the thermal conditions perceived by users. The outdoor spaces examined were a square with a parking area and urban canyons. One parking area was analysed in Pavones (see Figure 5(a)), and two in Fontarrón (Fontarrón 1 and 2, see Figure 5(b)). The urban canyons selected were two pedestrian streets with a height to canyon width (H/W) ratio of 1 in Fontarrón (see Figure 5(b)), and a parking area in Pavones with a H/W ratio of 0.5 (see Figure 5(a)). The aim was to check the impact of the renovation projects and identify the optimal strategies for rationalist urban typology.

The current state simulations (Table 5) show that the parking areas, which use black finishing material (asphalt), are where heat storage occurs, and the process is more intense during the summer months. The results shows that the system is sensitive to soil type, and thus the tool can be used to support the selection of materials. The main effect of urban geometry is in heat distribution and dissipation: heat dissipation occurs at a low height in the parking area, while in the urban canyon the dissipation depends on many factors, such as the H/W ratio, wind speed, façade orientation and exposure. Green areas, especially with tall trees, are those where lower temperatures, higher humidity and milder winds are recorded. The mitigating effect of vegetation is more relevant in the summer. This result also seems coherent with the actual changes that take place in outdoor urban spaces, as in the winter the effects of shading and evapotranspiration produced by trees, which are mainly deciduous, are less than in the summer.

An analysis of the various design scenarios was conducted to compare the thermal conditions of the current state with the results obtained from each simulation. The diverse results demonstrate a complexity of variables and processes involved in the microclimate of the urban space. The comparison shows that an increase in green areas produces an air temperature reduction and better thermal

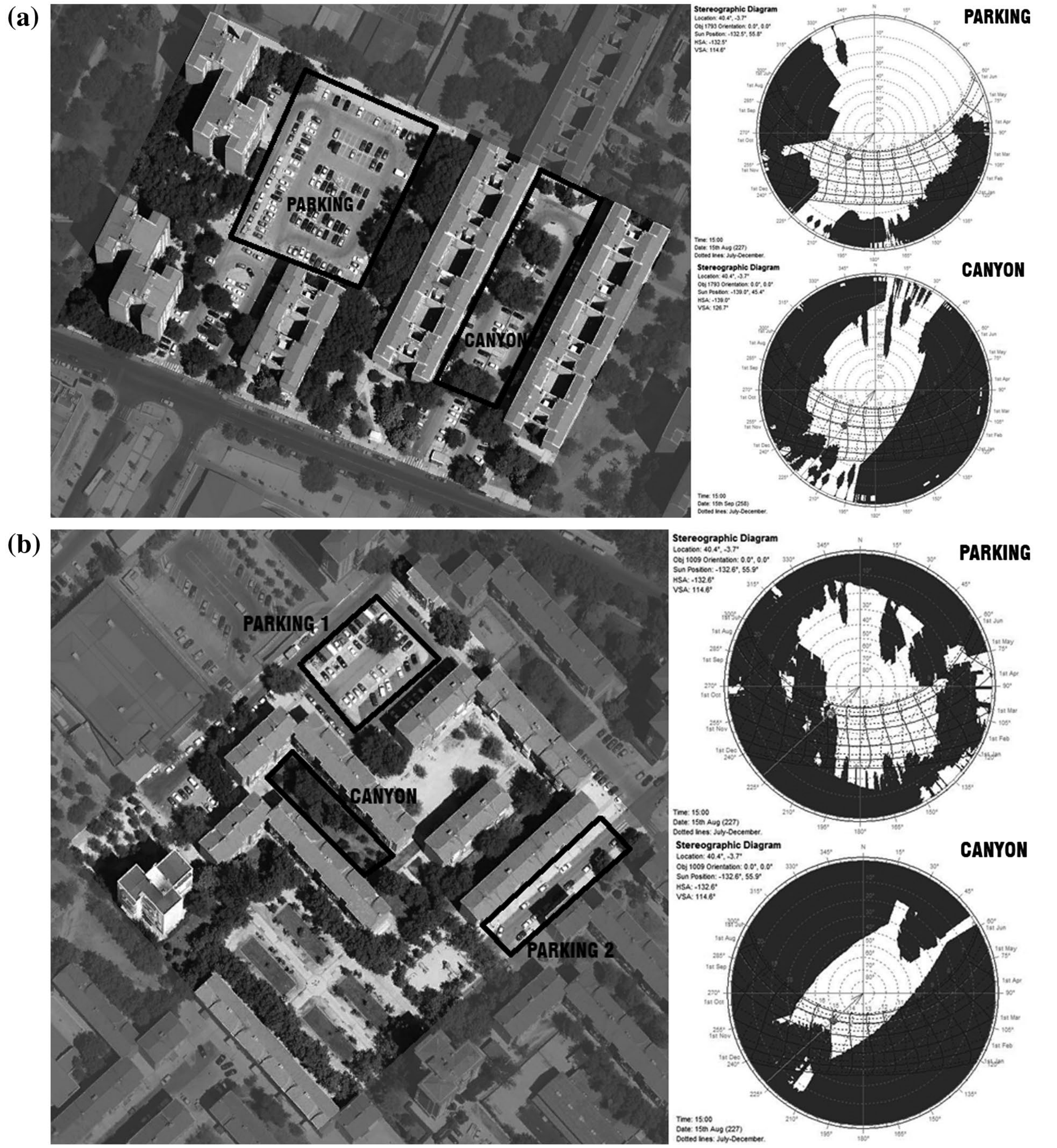

Figure 5. Aerial view and stereographic diagrams for (a) Pavones (b) and Fontarrón. Source: Googlemaps and authors (using Ecotect 2010).

comfort conditions, while changes in the soil cause an air temperature reduction but worsening thermal comfort conditions.

According to the results in the parking areas, the substitution of asphalt with Perfect Cool (scenario 2) results in worse thermal conditions than the current state (ΔUTCI=2.8), while the white asphalt (scenario 1) results in an enhancement of discomfort sensation equal to 0.6 in Fontarrón 1 and 1.1 in Fontarrón 2. The urban canyon behaviour is similar, even though the variations from the current state are lower, especially in the Fontarrón case studies In addition, scenario 3 (reducing the green area) causes an increase in thermal stress in Pavones (P.3) but an amelioration in Fontarrón (F1.3 and F2.3). The use of white asphalt and turf blocks in Fontarrón (F1.1 and F2.1) causes a reduction in Ta and an increase in Tmrt and thermal stress.

Only scenario (4), which increases the green area with tall trees, produces an air temperature reduction and

Table 5. Simulation results compaing the current state with the conditions projected for each scenario.

Number	Scenario	Ta (°C)	Tmrt (°C)	RH (%)	W (m/s)	UTCI (Ceq)
Parking area						
	Pavones					
PC	Current state	31.26	62.73	72	1.47	39.70
P2	Perfect Cool	29.94	55.65	63	1.10	42.50
P3	Green elimination	29.79	69.41	59	0.91	40.70
P5	Shrubs 30%	30.34	70.80	63	0.88	41.90
P4	Trees 30%	29.11	54.75	67	0.94	37.20
P6	Perfect Cool grass	27.70	60.20	75	0.76	37.30
	Fontarrón					
F1C	Current state	29.87	69.51	58	1.46	40.30
F11	White asphalt	27.66	78.00	61	1.26	40.90
F13	Green elimination	28.83	68.62	56	1.20	39.30
F15	Shrubs 30%	28.52	68.45	58	1.18	39.20
F14	Trees 30%	25.94	59.34	73	1.28	35.80
	Fontarrón 2					
F2C	Current state	29.60	69.39	66	1.59	40.50
F21	White asphalt	27.96	78.47	69	1.43	41.60
F23	Green elimination	28.83	68.62	56	1.20	39.30
F25	Shrubs 30%	28.26	59.35	68	1.15	37.40
F24	Trees 30%	26.72	32.33	77	1.38	29.80
Urban canyon						
	Pavones					
PC	Current state	31.26	62.73	72	1.46	42.00
P3	Green elimination	30.78	69.07	68	1.49	41.80
P6	Grass	29.45	54.28	85	0.98	39.10
P5	Shrubs 30%	30.49	54.00	79	1.03	39.50
P4	Trees 30%	29.08	31.06	82	1.15	32.80
	Fontarrón					
FC	Current state	27.70	62.34	58	0.27	37.70
F1	White asphalt	26.65	61.93	60	0.42	36.70
F3	Green elimination	27.14	67.91	56	0.43	38.20
F5	Shrubs 30%	26.70	61.94	59	0.42	36.70
F4	Trees 30%	26.21	61.76	61	0.42	36.40

Note: RH = relative humidity; Ta = air temperature; Tmrt = mean radiant temperature; UTCI = Universal Thermal Climate Index; W = wind speed.

results in thermal discomfort mitigation. The green area increase using tall trees is the best solution in terms of the reduction of Ta and UTCI difference, and thermal comfort amelioration. In the Pavones urban canyon (P.4) the UTCI reduction of 9.2°C is achieved, and in the Fontarrón parking (F2.4) it is greater than 10°C, passing from 'very strong heat stress' to 'moderate heat stress' (see Figure 6).

5. Discussion

The result of the climate data and UTCI analysis demonstrates that there is not a direct relationship between air temperature and thermal comfort perception, but that many factors are involved. The results of the thermal comfort analysis for the summer period show that the primary factor in Tmrt, which depends on multiplicity radiations and the ability to emit and absorb heat. In the urban environment, the radiation energy absorbed by pedestrians (which results in thermal perception) is derived mainly from a long wave domain that depends on the temperatures of surfaces and reflected waves, among other parameters [50].

The UTCI, thanks to its wide range of results, enables differentiation between even slight deviations in microclimate conditions; thus it is well suited to comparative analyses such as this one. The comparison of the six scenarios and the wide diversity of results shows that urban microclimate forecast is complex and requires a case-by-case analysis. The numerical approach may be useful and efficient in guiding designers in the decision-making phase to choose the most suitable solutions for renovation urban projects.

In terms of the renovation strategies proposed, increasing green areas produces a thermal discomfort mitigation effect due to the simultaneous occurrences of shade and evapotranspiration. The green areas improve the microclimate in both open areas (parking) and urban canyons. The rationalist urban typology in particular, with its high density and wide open areas, offers the opportunity to provide large green areas with tall trees. The reduction of spaces dedicated to car movement and parking is another strategy that can be used to improve the green area percentage in existing urban spaces.

Regarding the use of cool materials, the comparison shows two opposite effects at the same time: a reduction in Ta and an increment in the UTCI (see Table 5 and Figure 6). According to the results of [51],

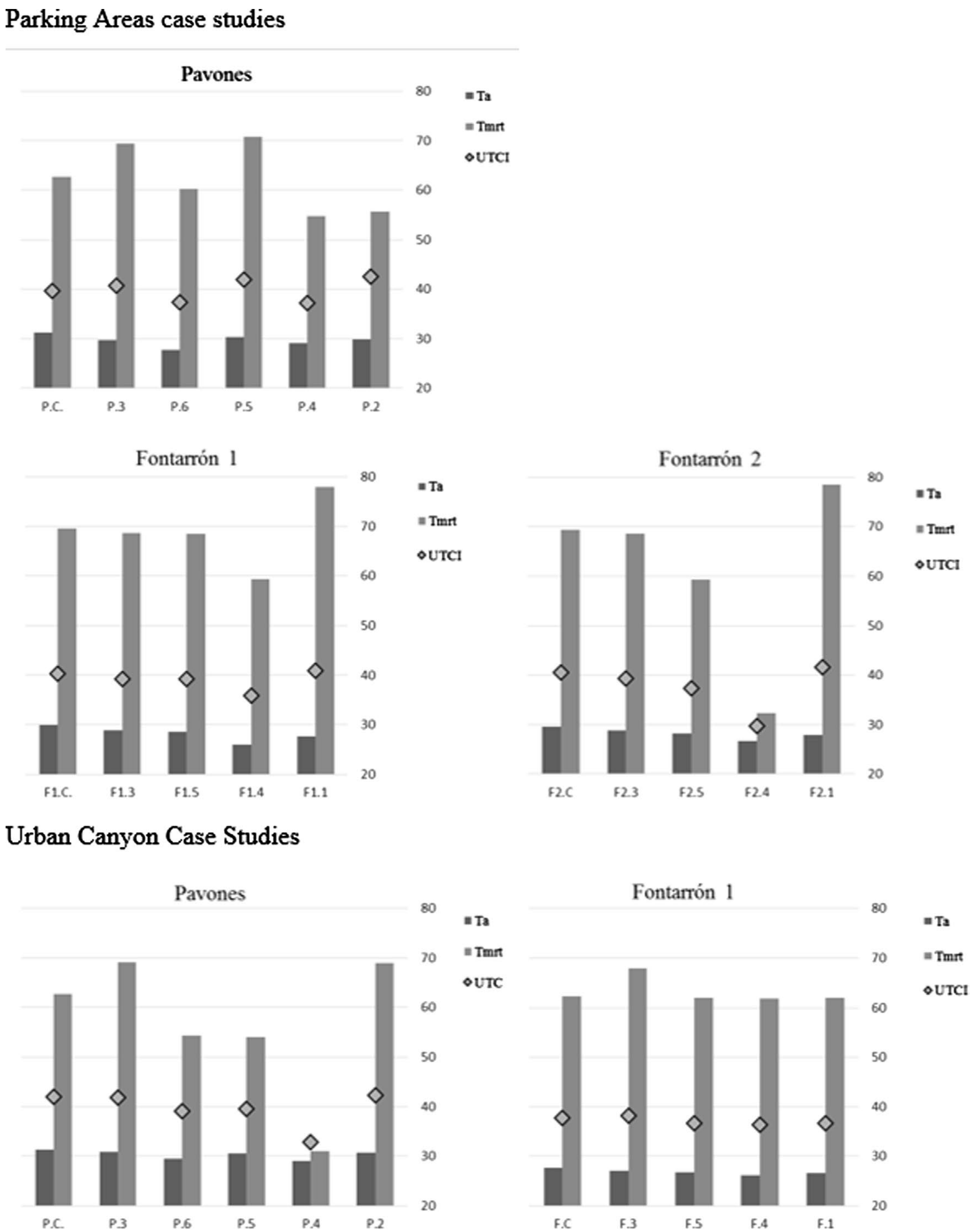

Figure 6 Results of the case study for parking areas and urban canyons: comparison of air temperature (Ta), UTCI and mean radiant temperature (Tmrt).

the simulation results show that the increase in ground albedo has the smallest influence on the microclimate, whereas the urban geometry is much more important. Finally, in terms of thermal comfort, the unfavourable outcomes obtained using cool materials suggest that renovation strategies in urban areas should be oriented towards improving green areas or providing better shading rather than changing the surface materials that are used.

6. Conclusions

This paper presents the results of a thermal comfort analysis carried out in order to investigate the effects of different urban renovation strategies on outdoor spaces using real case sudies. The present study is a contribution to the understanding of microclimate processes and the first step towards outdoor renovation strategies design which are focused on better thermal comfort in the built environment. It demonstrates the capability of CFD simulations to increase overall understanding of urban microclimate processes and to assist with forecasting the outcomes of different scenarios. Thermal simulations can be beneficial to urban planners when making decisions regarding the approach to take in urban renovation projects. As result of the study, it is possible to conclude that urban rationalist morphologies with tall building blocks, high density and wide open spaces can be successfully regenerated. By making a few changes, such as pavement replacement and path redesign, it is possible to improve thermal quality with little investment. In particular, actions taken in open spaces such as squares or parking areas can result in significant changes. On the other hand, changes made to urban canyons only produce slight variations in terms of air temperature and outdoor thermal comfort during the summer period.

In addition, the simulation results show that outdoor thermal comfort is more influenced by Tmrt than by Ta – thus, actions to mitigate thermal discomfort in urban spaces should involve a complex analysis of the wave domain encompassing the direct, reflected and surface temperatures.

Regarding outdoor space renovation, enhancing green areas using tall trees shows the most positive results in both parking areas and urban canyons, whereas the use of cool paving materials resulted in contradictory effects in this study, whereby the air temperature was reduced but at a cost of an increase in heat stress and thus thermal discomfort. According to [47], the use of highly reflective materials may expose citizens to the reflected radiation, resulting in increased discomfort.

The main innovation of this study was the application of its methodology – simple CFD simulations used for different scenarios with the UTCI as the comparison parameter – to a rationalist neighbourhood in Madrid. Although the present study is not sufficient for the definition of renovation strategies for outdoor spaces, it paves the way for future work on existing outdoor urban space renovation and its effects on the microclimate. Further studies on other urban environments, cities, climate conditions and season should be conducted to obtain a fuller understanding of the implication of outdoor space renovation and the thermal comfort levels that occur. The results of this first case study could be reproduced for similar neighbourhoods in Madrid as a first step to improving the understanding of the relations between urban morphology and microclimate behaviour.

Notes

1. The Köppen climate classification was developed by Russian and German scientist Wladimir Köppen in 1884, and is one of the most widely used climate classification systems.
2. White asphalt is a cool material used for the construction of roads and pavements. The material characteristics used for the simulation were a solar reflectance 0.55 and an emissivity value of 0.9 [47].
3. PerfectCool is a dark colored pavement coating with high albedo. Laboratory tests have revealed that PerfectCool can reflect up to 81% of near infrared waves, has a low heat conductivity of 0.252 W/mK, has a high albedo of 0.46 and an emissivity value of 0.828 [49].

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References

[1] The World Bank. *Building Urban Resilience*, The World Bank Group, Washington, DC, 2013. http://elibrary.worldbank.org/doi/book/10.1596/978-0-8213-8865-5.
[2] A. Dimoudi and M. Nikolopoulou, *Vegetation in the urban environment: microclimatic analysis and benefits*, Energy and Buildings 35(1) (2003), pp. 69–76.
[3] B. Givoni, *Climate Considerations in Building and Urban Design*, Thomson, New York, NY, 1998.
[4] I. Knez, S. Thorsson, I. Eliasson, and F. Lindberg, *Psychological mechanisms in outdoor place and weather assessment: towards a conceptual model*, International Journal of Biometeorology 53(1) (2009), pp. 101–111.
[5] M. Nikolopoulou (ed.), *Designing Open Spaces in The Urban Environment: A Bioclimatic Approach*, Centre for Renewable Energy Sources, Pikermi, 2004.
[6] M. Nikolopoulou and S. Lykoudis, *Use of outdoor spaces and microclimate in a Mediterranean urban area*, Building and Environment 42(10) (2007), pp. 3691–3707.
[7] M. Santamouris, N. Papanikolaou, I. Livada, I. Koronakis, C. Georgakis, A. Argiriou, and D.N. Assimakopoulos, *On the impact of urban climate on the energy consumption of buildings*, Solar Energy 70(3) (2001), pp. 201–216.
[8] I. Eliasson, I. Knez, U. Westerberg, S. Thorsson, and F. Lindberg, *Climate and behaviour in a Nordic city*, Landscape and Urban Planning 82(1–2) (2007), pp. 72–84.
[9] M. Nikolopoulou and S. Lykoudis, Thermal comfort in outdoor urban spaces: Analysis across different European countries, Building and Environment 41(11) (2006), pp. 1455–1470.
[10] I. Tumini, *The urban microclimate in open space. Case studies in madrid*, Cuadernos de Investigación Urbanística 96 (2014), p. 78.
[11] A. Matzarakis, F. Rutz, and H. Mayer, *Modelling radiation fluxes in simple and complex environments – application of the RayMan model*, International Journal of Biometeorology 51(4) (2007), pp. 323–334.

[12] A. Matzarakis, *Assessing climate for tourism purposes: Existing methods and tools for the thermal complex*, in *Proceedings of the first international workshop on climate, tourism and recreation*, A. Matzarakis and C.R. de Freitas, eds., Commission on Climate Tourism and Recreation, International Society of Biometerology, Porto Carras, 2001, pp. 101–112.

[13] H. Akbari, M. Pomerantz, and H. Taha, *Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas*, Urban Environment 70(3) (2001), pp. 295–310.

[14] P.A. Mirzaei and F. Haghighat, *Approaches to study urban heat island – abilities and limitations*, Building and Environment 45(10) (2010), pp. 2192–2201.

[15] M. Davies, P. Steadman, and T. Oreszczyn, *Strategies for the modification of the urban climate and the consequent impact on building energy use*, Energy Policy 36(12) (2008), pp. 4548–4551.

[16] F. Ali-Toudert and H. Mayer, *Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate*, Building and Environment 41(2) (2006), pp. 94–108.

[17] F. Gaja i Díaz, *Urbanismo sostenible, urbanismo estacionario. Ideas para la transición* [Sustainable Urbanism, stationary Urbanism. Ideas for the transition], Revista Digital Universitaria UNAM 10 (2009), available at http://www.revista.unam.mx/vol.10/num7/art41/int41.htm.

[18] J. A. Turégano Romero, *Arquitectura bioclimática y urbanismo sostenible* (volumen I) [Passive Architecture and Sustainable Urban Planning], Universidad de Zaragoza, Zaragoza, 2009.

[19] M. Valenzuela Rubio, *Ciudades y sostenibilidad: el mayor reto urbano del siglo XXI* [Cities and sustainability: the biggest urban challenge of the XXI century], Lurralde: Investigacion y Espacio 32 (2009), pp. 405–436.

[20] L. A. Cardenas Jiron, *Planificacion De La Forma Urbana Con Criterios De Eficiencia Energetica: caracterización de patrones bioclimáticos en tejidos urbanos residenciales* [Planning urban morphology with energy efficiency criteria: characterization of climate patterns of residential urban grid], Universidad Politécnica de Madrid, Madrid (2010), p. 354.

[21] R. Giridharan, S.S.Y. Lau, S. Ganesan, and B. Givoni, *Urban design factors influencing heat island intensity in high-rise high-density environments of Hong Kong*, Building and Environment 42(10) (2007), pp. 3669–3684.

[22] X. Picot, *Thermal comfort in urban spaces: impact of vegetation growth case study: Piazza della Scienza, Milan, Italy*, Energy and Buildings 36(4) (2004), pp. 329–334.

[23] M. Nikolopoulou, N. Baker, and K. Steemers, *Thermal comfort in outdoor urban spaces: Understanding the human parameter*, Solar Energy 70(3) (2001), pp. 227–235.

[24] L. Chen and E. Ng, *Outdoor thermal comfort and outdoor activities: A review of research in the past decade*, Cities 29(2) Apr. (2012), pp. 118–125.

[25] Ashrae, *ASHRAE Handbook. Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta GA, Atlanta, GA, 2005.

[26] G. Havenith, Individualized model of human thermoregulation for the simulation of heat stress response, Journal of Applied Physiology (Bethesda, Md. 1985) 90(5) May (2001), pp. 1943–1954

[27] V. Candas, *To be or not to be comfortable: basis and prediction*, Elsevier Ergonomics Book Series 3 (2005), pp. 207–215.

[28] D. Fiala, G. Havenith, P. Bröde, B. Kampmann, and G. Jendritzky, *UTCI-Fiala multi-node model of human heat transfer and temperature regulation*, International Journal of Biometeorology 56(3) (2012), pp. 1–13.

[29] P. Bröde, E.L. Krüger, F.A. Rossi, and D. Fiala, *Predicting urban outdoor thermal comfort by the Universal Thermal Climate Index UTCI – a case study in Southern Brazil*, International Journal of Biometeorology 56(3) (2012), pp. 471–480.

[30] P. Höppe, *Different aspects of assessing indoor and outdoor thermal comfort*, Energy and Buildings 34(6) (2002), pp. 661–665.

[31] D. Robinson, *Computer Modelling for Sustainable Urban Design: Physical Principles, Methods, and Applications*, Routledge, Oxford, 2011.

[32] M. Samaali, D. Courault, M. Bruse, A. Olioso, and R. Occelli, *Analysis of a 3D boundary layer model at local scale: Validation on soybean surface radiative measurements*, Atmospheric Research 85(2) (2007), pp. 183–198.

[33] J.A. Acero and K. Herranz-Pascual, A comparison of thermal comfort conditions in four urban spaces by means of measurements and modelling techniques, *Building and Environment*, 93 (2015), pp. 245–257,

[34] J. Allegrini, V. Dorer, and J. Carmeliet, *Influence of morphologies on the microclimate in urban neighbourhoods*, Journal of Wind Engineering and Industrial Aerodynamics 144 (2015), pp. 108–117.

[35] M. Bruse, ENVI-met website, available at http://www.envimet.com, 2004.

[36] M. Kottek J. Grieser, C. Beck, B. Rudolf, and F. Rubel. *World Map of the Köppen-Geiger climate classification updated*. Meteorol. Z., 15 (2006), pp. 259–263.

[37] M. Bruse and H. Fleer, *Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model*, Environmental Modelling & Software 13(3-4) (1998), pp. 373–384.

[38] Aemet, *Iberian climate atlas*, Agencia Es, Madrid, 2011

[39] S. Rueda, *"Plan Especial de Indicadores de Sostenibilidad Ambiental de la Actividad Urbanística de Sevilla"* [Special Planning of Environmental Sustainability Indicators for Urban Activities in Seville], Gerencia de Urbanismo, Ayuntamiento de Sevilla, Barcelona, 2006.

[40] S. Rueda, *Compacidad* [Compacity], Ambiente 102 (2010), p. 2012.

[41] S. Hassid, M. Santamouris, N. Papanikolaou, A. Linardi, N. Klitsikas, C. Georgakis, and D.N. Assimakopoulos, *The effect of the Athens heat island on air conditioning load*, Energy and Buildings 32(2) (2000), pp. 131–141.

[42] S.K. Meyn and T.R. Oke, *Heat fluxes through roofs and their relevance to estimates of urban heat storage*, Energy and Buildings 41(7) (2009), pp. 745–752.

[43] I. Tumini, *The Urban Microclimate in Open Space: Case Studied in Madrid*, Cuadernos de Investigación Urbanística 96 (2014). pp. 1–73.

[44] S. Berkovic, A. Yezioro, and A. Bitan, *Study of thermal comfort in courtyards in a hot arid climate*, Solar Energy 86(5) (2012), pp. 1173–1186.

[45] I. J. Miron, J. J. Criado-Alvarez, J. Diaz, C. Linares, S. Mayoral, and J.C. Montero, *Time trends in minimum mortality temperatures in Castile-La Mancha (Central Spain): 1975–2003*, International Journal of Biometeorology 52(4) (2008), pp. 291–299.

[46] P. T. Nastos and A. Matzarakis, *The effect of air temperature and human thermal indices on mortality in Athens, Greece*, Theoretical and Applied Climatology 108(3–4) (2012), pp. 591–599.

[47] M. Santamouris, A. Synnefa, and T. Karlessi, *Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions*, Solar Energy 85 (2011), pp. 3085–3102.

[48] E. Higueras, Urbanismo bioclimático, Cuadernos de Investigación Urbanística 24 (2011), pp. 1–79.

[49] W. C. Wan, W. N. Hien, T. P. Ping, and A. Z. W. Aloysius, *A Study on the effectiveness of heat mitigating pavement coatings in Singapore*," in Journal of Heat Island Institute International 7 (2012), available at http://www.heat-island.jp/web_journal/HI2009Conf/pdf/35.pdf.

[50] N. Kántor and J. Unger, *The most problematic variable in the course of human-biometeorological comfort assessment – the mean radiant temperature*, Central European Journal of Geosciences 3(1) (2011), pp. 90–100.

[51] E. Andreou, *Thermal comfort in outdoor spaces and urban canyon microclimate*, Renewable Energy 55 Jul. (2013), pp. 182–188.